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LANDING ON EUROPA: CHALLENGES, TECHNOLOGIES, AND A STRATEGY

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Jupiter's moon Europa is of intense scientific interest because of the vast quantities of salty liquid water which likely lay beneath its thin icy crust and the tantalizing prospect of finding life elsewhere in the solar system. The planned Europa Mission, which would perform remote science through multiple flybys of Europa, is under development and promises to yield unprecedented insight into this intriguing body. However, there remains a strong desire in the scientific community to perform in situ Europa science through a landed mission. Europa presents unique challenges to a landing mission because of its hostile radiation environment and the lack of information about its terrain. As a complement to the flyby mission, a bold concept to land on Europa and perform in situ science is being studied. Such a mission requires significant technology development to overcome the inherent landing challenges. This paper provides a brief overview of the Europa Lander mission concept and its notional objectives. It then describes the significant challenges associated with landing on Europa, the technologies required to overcome those challenges, and a strategy for Deorbit, Descent, and Landing.

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INTRODUCTION

As the interest in Jupiter's moon Europa grows, so does the desire to perform in situ science on the surface of this body. However, the difficulties of getting to Europa and subsequently landing safely on Europa make a landed Europa mission uniquely challenging.

We have identified a number of major challenges to the Deorbit, Descent, and Landing phase of the Europa Lander mission concept. Briefly,

- Terrain Uncertainty: Little is known about the surface topography and composition of Europa, so a landed mission must be robust to a wide variety of terrain types.
- Delivery Uncertainty: NASA's planned Europa flyby mission currently in development and scheduled for launch in 2022 is expected to provide high-resolution images of a number of regions of scientific interest. These images will also be used for site selection for a potential Europa Lander, partially mitigating the concern about landing hazards. However, the landing accuracy of missions to date exceeds the accuracy required to make use of high-resolution Europa images.
- Radiation: Europa is bathed in the radiation of Jupiter's radiation belt. Radiation can permanently damage electronics and may result in damage to other materials (e.g., propellants) for which performance and predictability are critical.
- Planetary Protection: A landed Europa mission would be required to comply with NASA planetary protection requirements which essentially prohibit contamination of Europa by even a single microorganism.
- Site Contamination: In order to perform in situ science, we must ensure that the lander (and delivery vehicle) do not contaminate the landing site.
- Mass: The launch mass to landed mass ratio for a Europa lander is approximately 50-to-1 (i.e., for every kilogram delivered to the surface of Europa, approximately 50 kg of launch mass is required).

We discuss the first four challenges listed above in more detail in a subsequent section.

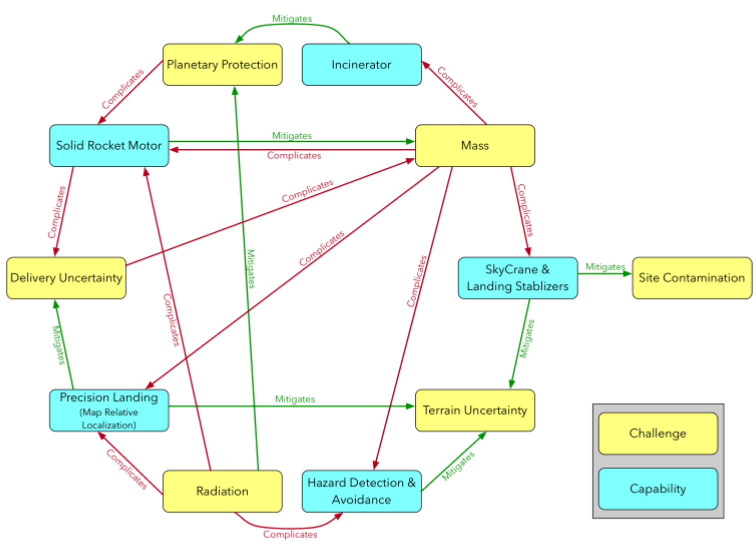

Figure 1: Challenges and Capabilities for the Deorbit, Descent, and Landing of the Europa Lander Concept

For the Europa Lander concept, we have chosen a number of capabilities which are intended to mitigate the challenges described above. Some of these capabilities are new and will require significant technology development (e.g., Hazard Detection and Avoidance), some have been in development for years and will fly on other missions prior to landing on Europa (e.g., Terrain Relative Navigation), and others have flown before but will require tailoring to function properly in the Europan environment and to meet the requirements of the Europa Lander concept (e.g., the solid rocket motor for the Deorbit Burn). Not surprisingly, there is not a one-to-one mapping between challenges and capabilities—some capabilities partially mitigate multiple challenges, as illustrated in Figure 1. Also not surprisingly, many of the capabilities intended to mitigate certain challenges are also subject to the challenges listed above; this is indicated by the numerous connections between challenges and capabilities in Figure 1.

In this paper we emphasize certain capabilities (Hazard Detection and Avoidance, Precision :anding, and SkyCrane and Landing Stabilizers,) at the expense of other capabilities needed for landing which are either more mature (e.g., the solid rocket motor) or are of less interest to a GN&C community.

Figure 2 is a simplified version of Figure 1 which illustrates just those capabilities and challenges discussed in this paper.

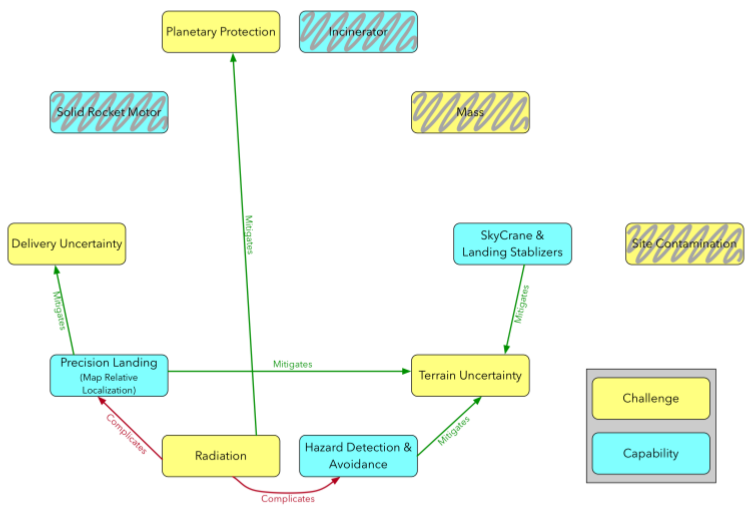

Figure 2: Challenges and Capabilities discussed in this paper

EUROPA LANDER MISSION CONCEPT

Following the Europa mission's projected launch in 2022, the Europa Lander concept mission would launch on a separate launch vehicle no earlier than 2025. An example scenario launches the flight system consisting of a Carrier spacecraft and a Lander from Kennedy Space Center and follows a ΔV-leveraged Earth Gravity Assist (ΔV-EGA) trajectory to Jupiter. Two ΔV-EGA launch opportunities to Jupiter open within approximately two months of each other and repeat roughly every thirteen months with the synodic period between Jupiter and Earth. An example trajectory launches on October 16, 2025, followed by a deep space maneuver (DSM) on November 1, 2026, after which the spacecraft encounters Earth for a gravity assist on December 5, 2027 and arrives at Jupiter on July 7, 2030; Figure 3 shows this example trajectory. The backup launch period for this trajectory opens two months after the first launch period closes with an example launch on January 5, 2026, DSM on January 14, 2027, Earth-gravity assist on November 14, 2027, and arrival at Jupiter on November 12, 2030. Additional backup opportunities exist eleven and thirteen months later, respectively. This trajectory benefits from a high (0.89 AU) perihelion, but the Space Launch System (SLS) launch vehicle would likely be required to provide sufficient performance due to the likely large spacecraft mass at launch.

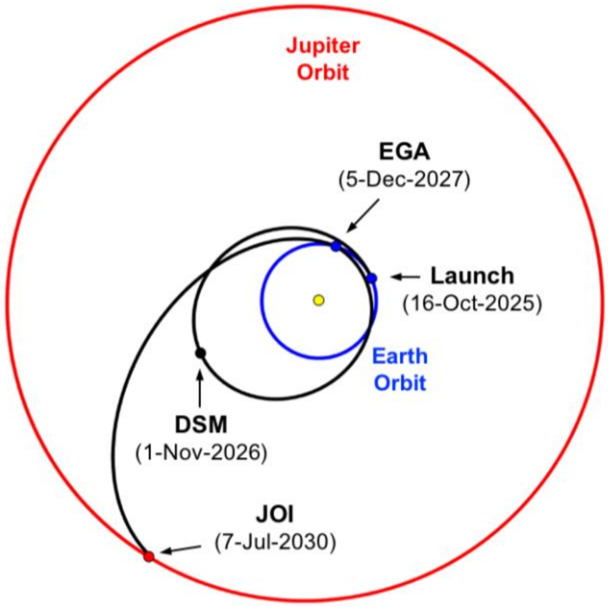

Figure 3: Example 2025 ∆V-EGA with 4.7 year transfer time

On approach to Jupiter, the tour trajectory would begin with a Ganymede gravity-assist prior to the Jupiter Orbit Insertion (JOI) maneuver capturing into a 200 day orbit. At apoapsis, a Peri-Jove Raise (PJR) maneuver would set up the next gravity assist at Ganymede. Such an example tour trajectory would be designed to reduce the spacecraft velocity relative to Europa which would enable an efficient landing while minimizing the fuel requirements and the spacecraft's exposure to Jupiter's radiation. Consequently, the tour would consist of a series of gravity assists of Callisto and Ganymede and would only encounter Europa at the very end of the tour, more than 18 months after JOI. Figure 4 shows a representative trajectory for the Jupiter tour of the mission[1].

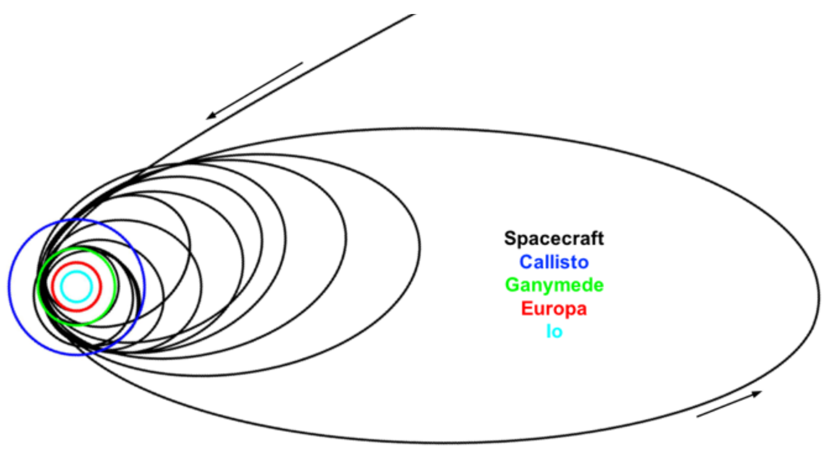

Figure 4: Example tour trajectory showing Jupiter arrival and transition to Europa

The first Europa gravity assist would mark the beginning of the final mission phase before landing, and the spacecraft would then be exposed to much higher daily radiation doses. The first Europa gravity assist would be designed to insert the spacecraft into a Europa-resonant orbit and ΔV-leveraging maneuvers would be used to further reduce the spacecraft's velocity relative to Europa[2]. This velocity reduction would make the low-energy (or three-body) regime accessible to the spacecraft, in which the gravitational interplay of Europa and Jupiter would enable the Carrier spacecraft to linger in the vicinity of Europa for the full duration of the surface mission. This final part of the tour trajectory from first Europa flyby to landing would take approximately one month and would set up the Lander delivery to a 5 km periapsis altitude at a target state relative to the landing site.

Shortly before landing, the Lander spacecraft would separate from its Carrier, after which the Carrier would function as a telecommunications asset to relay the Lander signal to Earth. While the Carrier would transfer to its relay orbit, the Lander would proceed to its target. Various Carrier relay orbits are currently being studied and the selection will take into consideration landing site accessibility, post-landing telecommunications visibility, and range between Carrier and Lander, as well as fuel requirements, radiation exposure, and planetary protection factors. Figure 5 shows an example trajectory for final approach to Europa, Lander delivery, Carrier transfer, and relay orbit in the Jupiter-Europa rotating frame.

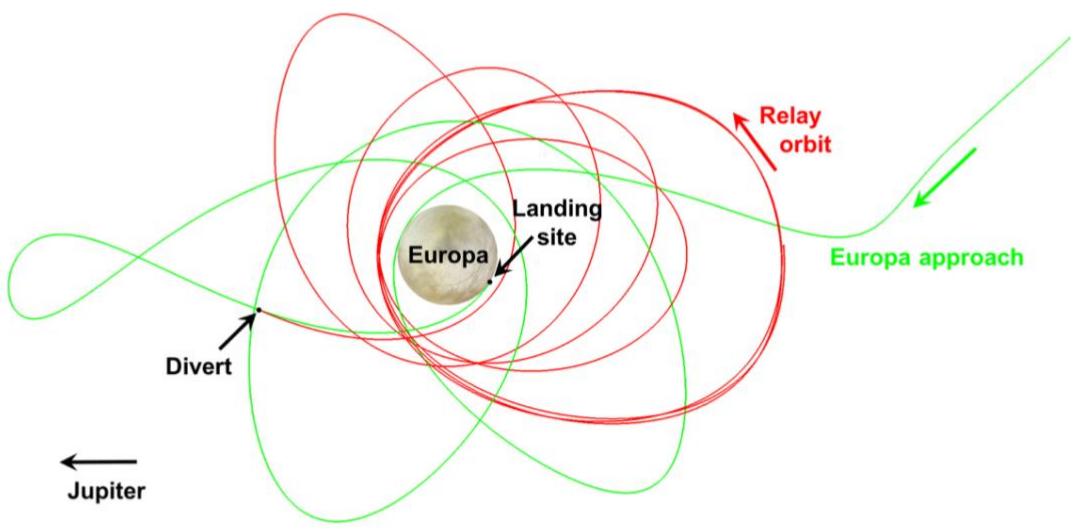

Figure 5: Example trajectory for Lander delivery and relay orbit

The Deorbit, Descent and Landing (DDL) Phase begins when the Lander separates from the Carrier, approximately 2.5 hours prior to landing and is described in more detail in subsequent sections.

Mission Goals

With a massive liquid water ocean beneath its icy crust, Europa is one of the Solar System's prime candidates for hosting life. As such, the mission goals for the science community are to

1. Search for evidence of life on Europa
2. Assess the habitability of Europa via in-situ techniques uniquely available to a lander mission

3. Characterize surface and subsurface properties at the scale of the lander to support future exploration

ANTICIPATED DDL CHALLENGES

Europa presents a number of significant natural and self-imposed challenges for landing. In this section we describe a number of challenges which are of particular concern to GN&C.

Terrain Uncertainty

Little is known about the surface topography of Europa. Imagery of the surface has been acquired by multiple spacecraft (Pioneer 10, Voyagers 1&2, Galileo, Cassini, and New Horizons) over the past forty-four years. Global maps generated from the highest resolution imagery available, primarily from Galileo, include 36% coverage of the European surface at resolutions of 1 km/pixel. A few highly localized areas have been imaged at resolutions better than 50 m/pixel. Direct observation of surface topography is available thanks to a small handful of image pairs suitable for stereo digital elevation map (DEM) processing, however these DEMs are limited to resolutions of several hundred meters per pixel.

In the absence of direct observations at the scales required for terrain relative localization (~6 m/pixel), landing (>1 m/pixel), and surface sampling (>1 cm/pixel), we must rely on a range of unverifiable techniques to provide a best estimate of the terrain that may be encountered on the Europan surface. Such techniques include: extrapolation from lower-resolution data using self-similarity, fractal, or chaos theories; the use of analog terrains such as terrestrial arctic sea ice or lunar regolith; and theoretical modeling via physics-based simulations of postulated surface processes.

This terrain challenge for landing on Europa is unlike that of recent Mars landing missions, which have benefitted from a wealth of orbital reconnaissance data providing topographical data at or near the relevant length scales for landing, and more like the challenges faced by Viking. The current Europa Lander mission concept is expected to launch before any additional reconnaissance is performed of the Europan surface, necessitating that the entire design and development of the DDL mission phase be conducted relative to a surface that is both unknown and unknowable. In order to proceed it is necessary to formulate a set of terrain specifications which the DDL sequence will be designed to accommodate. This set of terrain specifications is effectively a contract that the program and its sponsors can agree to, design for, and test against.

New reconnaissance of candidate landing sites at high resolution will become available once the Europa mission reaches Europa. This will occur several years after the launch of Europa Lander and several years before landing. As there can be no guarantee that actual topography falls within the envelope of the design-to terrain specifications, derived data products will be used to verify the performance of the as-built DDL system against the actual landing site topography while it is already on-route to its target. This new reconnaissance will be orders of magnitude better than currently available surface data but will still not provide information at the sub-meter resolutions necessary to fully identify surface hazards that may preclude successful landing and/or surface sampling.

Several significant terrain risks are necessarily present in this approach, but multiple capabilities are included in the baseline design to mitigate these risks. The combination of Map Relative Localization and Precision Landing allow us to fly to within fifty meters of a chosen location within the reconnaissance zone. This enables us to choose a landing site that has been identified as "safe" based on Europa mission reconnaissance and the as-built capabilities of the landing system, presuming that such a site exists. Further, the use of Hazard Detection and Avoidance (HDA) allows us to identify and avoid hazards below the resolution of the Europa mission's reconnaissance data.

Delivery Error

In the current concept, Europa Lander approaches Europa at the start of DDL with a surface-relative velocity of about 1950 m/s. As described later, this velocity is largely nulled during the deorbit burn using a solid rocket motor. It is anticipated that the vehicle will be delivered to the start of the deorbit burn with an along-track *position error* of about ±4500 m (3σ) (cross-track and radial position errors will be significantly smaller), which roughly corresponds to the semi-major axis of the landing ellipse if no additional position errors were introduced.

As mentioned above, little is known about the topography and composition of Europa's surface, but it is the collective opinion of planetary scientists and engineers working on this concept that it is unlikely we will find a 9 km long region on Europa which is both accessible and safe to land.

This challenge is further exacerbated by uncertainties in the solid rocket motor thrust which contribute as much ±4 km (3σ) in along-track position error at deorbit burn termination.

Radiation

Being the largest and most powerful of any planetary magnetosphere in the solar system, Jupiter's magnetosphere traps and accelerates particles in a torus-like structure of radiation belts, which present a serious hazard for spacecraft. Since Europa orbits Jupiter well within the high-radiation zone, radiation exposure to the Lander can only be minimized but not avoided. Europa Lander would use a two-pronged approach to minimize the resulting damage to instruments and the spacecraft as a whole: trajectory design and radiation shielding. Trajectory design can minimize the exposure by avoiding the high-radiation areas as much as possible. The early part of the trajectory at Jupiter stays outside of the radiation belts as long as possible, only approaching Europa and thus the high-radiation zone shortly before landing. Based on the current mission design trajectories and the GIRE-2p Jovian radiation model, the Lander is expected to experience a total ionizing dose (TID) of ~1.7 Mrad, primarily from electrons, behind 100 mil of aluminum (Si equivalent). Radiation shielding provides additional protection against the environment. To attenuate the expected Lander dose to 150 krad (Si), most Lander and payload electronics are housed in a radiation vault similar to that used on Juno and planned for the Europa mission. Shielding by the Lander vault would decrease the expected TID to 150 krad (Si) or less. All electronics within the vault are rated to 300 krad to maintain a radiation design factor of two (RDF = 2).

It must also noted be that as compared to other missions where the rate of accumulation of dose is nearly uniform throughout the mission lifetime, for the Europa Lander a majority of the dose (both TID and displacement damage) is accumulated in the end-phase of the mission. Consequently, this presents an additional challenge to sensors and electronics with respect to their performance. Typically, sensors and electronics are required to provide full-performance at the beginning of life, and as they accumulate more dose, are expected to degrade causing performance to be at best marginal towards end-of-life. For the Europa Lander concept, the long non-operational cruise duration coupled with the short and abrupt DDL phase implies that the time at which the best performance is required from the sensors and electronics coincides with the end-of-life or end-of-lander mission segment. This atypical performance need is likely to require special radiation mitigation strategies such as power scheduling, annealing and/or intermittent trending of sensitive electro-optical and avionics components.

Planetary Protection

Europa Lander would have to comply with NASA planetary protection procedural requirements[3] and, as an anticipated Category IV mission, the probability of contamination (defined as the introduction of a single viable terrestrial microorganism) must be less than 10^{-4}. The calculation of this probability considers a number of factors including the bioburden at launch, the survival of contaminating organisms during the Cruise to Jupiter as well as in the radiation environment of Europa, the probability of an accidental Europa impact, the probability of successfully landing and surviving on Europa, and several others.

The implication of the planetary protection requirements on DDL—and in particular on the GN&C hardware elements of DDL—is that these hardware elements either must never reach the surface of Europa or that they must be sterile before they reach the surface of Europa. Ensuring that the hardware elements never reach Europa is a practical impossibility, so measures must be taken to ensure that they are sterile. Due to the complexity and size of the flight system, no single approach to sterilization is appropriate and therefore the planetary protection strategy is likely to consist of several sterilization techniques including cleaning and dry-heat microbial reduction (DHMR), and for components which can neither be cleaned nor heated, incineration devices on-board the vehicle would be considered to destroy any residual biological material prior to reaching the surface.

CAPABILITIES FOR EUROPA DDL

Precision Landing with TRN

The selection of the landing site for a science platform designed to explore the surface of a planetary body is a complex process that is driven by several considerations: reachability of the area by the landing system, science value of the targeted area, spacecraft safety during descent and touchdown, and operability during the science mission (fields of view for power, imaging, and communications, illumination, traversability for rovers, etc.). During this landing site selection process engineers and scientists require detailed knowledge of the engineering characteristics and capabilities of the spacecraft and of the candidate landing sites (topography/relief, soil mechanics, science markers, etc.).

Unfortunately, we have currently little information on Europa's surface characteristics that could help influence the design of the Lander to maximize the probability of finding landing sites that are safe and scientifically interesting. For example, we do not have statistics on the sizes and frequency of contiguous areas of high scientific value on Europa's surface. The same is true for areas that are safe for descent and touchdown and that could support efficient operations after landing. What's more, the appropriate information will not be available until the Europa mission collects the required data, which will happen after the launch of the Europa Lander mission.

To mitigate this challenge, the DDL team baselined a Precision Landing capability to dramatically reduce the size of the landing region (the area where the Lander is most likely to touchdown and come to a rest): the smaller the size of the landing region, the more likely for Europa to have landing areas that satisfy the given science and engineering constraints within them.

This Precision Landing capability employs Terrain Relative Navigation (TRN) to reduce the landing region size from kilometers to approximately one hundred meters. It uses a visual camera, an on-board map of the landing area, and computer vision algorithms running on a dedicated processor to first determine precisely the lander position; this information is then fed to a guidance algorithm that re-plans the trajectory to steer the lander to the target.

Hazard Detection and Avoidance

While Precision Landing has great potential to mitigate most of the risks of landing on challenging and scientifically relevant terrains on the surface of Europa, the resolution of the images that will be taken by the Europa mission and that will be used in the selection of the Europa Lander landing site, will not be sufficient to determine with high probability that there are no landing hazards at the Lander scale (i.e., 0.5 m roughness). In order to address this shortcoming, the DDL team has incorporated a Hazard Detection and Avoidance (HD&A) capability to the lander design. This capability consists of a 3D lidar which generates a point cloud of the terrain topography and which is then processed on-board to determine landing hazards. Based on this information, a guidance law generates a new trajectory to the closest safe landing spot.

SkyCrane with Landing Stabilizers

The Hazard Detection and Avoidance and Precision Landing capabilities described above have the purpose of minimizing the probability of landing on rough terrain. To provide graceful degradation and improved safety margins, the DDL team also investigated ways to improve, over the more traditional mechanical approaches of the past, the robustness of the lander touchdown system for successfully handling such rough terrain. To that end, the team began by reviewing previous touchdown systems for Lunar and Mars missions, from legged landers with passive shock absorbers, to landing pallets, airbags, and the SkyCrane system developed and used successfully by the Mars Rover Curiosity in 2012.

During the development of Curiosity's SkyCrane landing system, the engineering team discovered that the SkyCrane architecture–by keeping the descent engines far from the surface and thus reducing the negative effects of the engine plumes acting on the dusty planet surface and by decoupling the touchdown dynamics of the rover from the dynamics of the propulsive Descent Stage– enabled an order of magnitude reduction in the touchdown velocity when compared to previous landers such as Viking (an additional benefit of the SkyCrane architecture is that, by maintaining distance between the descent engines and the ground, it minimizes site contamination from propellant decomposition). A lower touchdown velocity not only increased the landing stability of the rover but it also decreased the potential for impact damage at touchdown due to excessive loads. Another observation from Curiosity's SkyCrane experience was that its mobility system (wheels and rocker-bogie suspension) behaved as an excellent landing gear thanks to its capability to contour itself around uneven terrain.

The Europa Lander study team, based on the Curiosity experience, adopted early on the SkyCrane architecture and set up to design a landing gear that extended the terrain contouring nature of Curiosity's mobility system to a fixed lander platform. For this later purpose, the team is investigating a concept in which the rover wheels are replaced by legs with footpads but unlike previous landers, these legs have low friction degrees of freedom (DOF) that allow them to "deform" during touchdown so that they adapt and contour to the moon's uneven surface while the SkyCrane pendulum dynamics keep the lander level with respect to the gravity vector, while descending vertically at a velocity of about 0.5 m/sec. When the belly pan of the lander touches down on the surface of the moon a sensing system autonomously triggers a pyrotechnically driven locking mechanism that freezes the legs in place. The result is a lander leveled with respect to the vertical, with its belly pan resting on the surface, and the legs acting as stabilizing outriggers (Figure 6).

Based on this basic concept the team is currently exploring design variations (number of legs, number of DOF per legs, touchdown triggers, locking mechanisms, etc.) to maximize system performance in the presence of extreme uneven terrain and non-zero landing horizontal velocity while minimizing mass, packaging volume, and complexity. Initial ADAM simulation results of the current architecture have shown promising results prompting its adoption as part of the Europa Lander baseline.

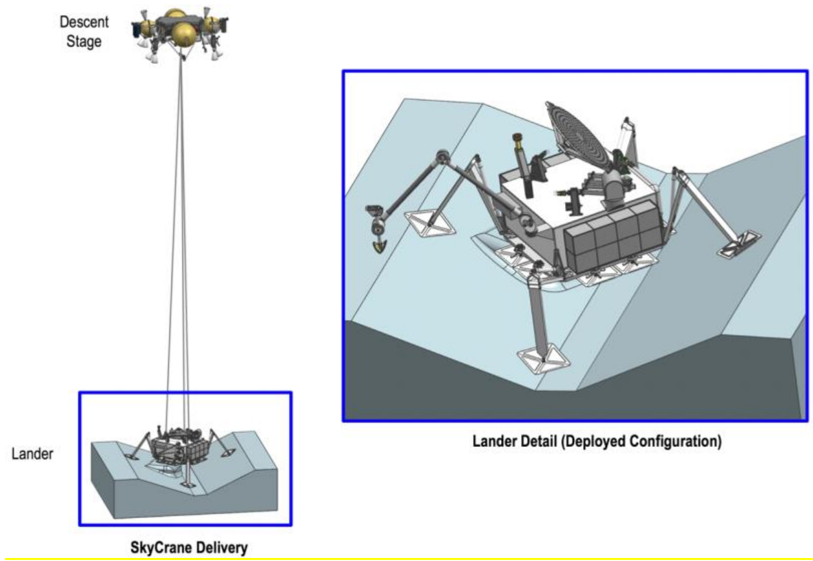

Figure 6: Example configuration of the Lander employing stabilizers in uneven terrain following delivery by Sky Crane

PROPOSED DEORBIT, DESCENT AND LANDING STRATEGY

In the notional timeline, the Deorbit, Descent and Landing (DDL) Phase begins when the Deorbit Vehicle (DOV) separates from the Carrier and Relay Stage (CRS), approximately 2.5 hours prior to landing. DDL ends shortly after Touchdown. DDL is comprised of several sub-phases, each of which is described below in sequential order.

Flight System

Figure 7 shows the elements of the flight system relevant to the DDL phase. Specifically, the Cruise Vehicle (CV) consists of the Carrier & Relay Stage (CRS) and the Deorbit Vehicle (DOV). The DOV separates from the CRS at the beginning of the Deorbit, Descent, and Landing (DDL) phase, after which the CRS repositions itself for relay operations. The DOV in turn consists of the Deorbit Stage, Descent Stage, and Lander, with the latter two forming the Powered Descent Vehicle (PDV) after separating from the Deorbit Stage. The PDV would deliver the Lander to the surface via a SkyCrane (described earlier), after which the Descent Stage is discarded.

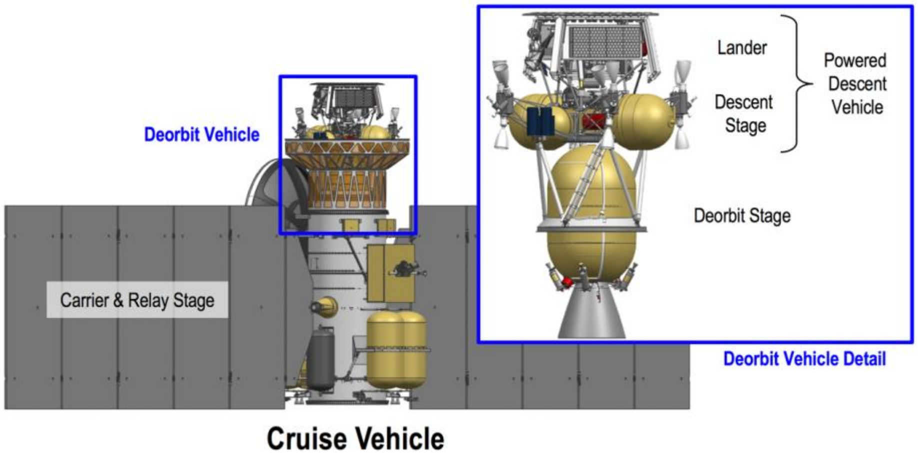

Figure 7: DDL-relevant elements of the Europa Lander concept flight system

Timeline

The duration of DDL is approximately 2.5 hours. However, most of that time is spent in the relatively benign Coast subphase. The solid rocket motor (SRM) burn duration is approximately 72 sec and the time from SRM burnout to Touchdown can take as long as four minutes, so the period of high dynamic activity lasts about five minutes.

A diagram illustrating the major subphases of DDL is shown in Figure 8.

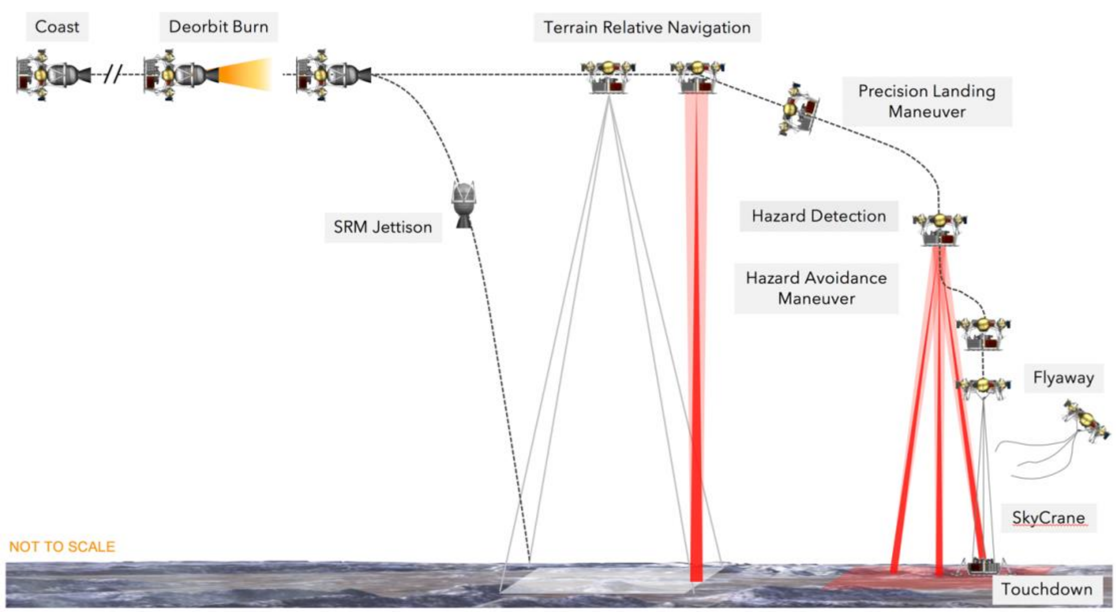

Figure 8: Major subphases envisioned for the Europa Lander mission concept

Coast

Following separation from the CRS, the DOV enters the Coast subphase. This phase begins with a rate damping period during which the vehicle nulls any attitude rates imparted during the Carrier Separation event, after which the vehicle maintains three-axis attitude using the reaction control system (RCS) for pointing and an inertially-propagated attitude estimate (the DOV is initialized with the inertial attitude from the CRS immediately prior to Carrier Separation and propagates this attitude until Touchdown using an IMU). At a sequenced time, the DOV will slew to the Deorbit Burn attitude and will maintain this attitude until SRM ignition.

Deorbit Burn

At a commanded time, the DOV will ignite the solid rocket motor (SRM) which will be used to reduce the Europa-relative velocity from 1950 m/s to 100 m/s. The SRM is a large motor which produces a nominal thrust of 44,000 kN and burns for approximately 72 sec until all of the solid propellant is consumed. During the Deorbit Burn, the DOV uses four dedicated MR-104 engines for pitch/yaw control while the long axis of the vehicle is steered using either descent engines or the reaction control system (RCS) thrusters. Nominally, SRM Ignition occurs at an altitude of 5 km above the surface of Europa and a distance of approximately 60 km up-track of the targeted landing location. DDL will be designed so that SRM Burnout occurs approximately 6 km up-track of the targeted landing location. The Deorbit Burn is a guided burn which will be designed to significantly reduce known delivery errors, but because of thrust variations of up to ±5% during the burn as well as position uncertainty at SRM ignition, along-track position error (relative to the targeted burnout position) at SRM Burnout can be as large as ±4 km. Furthermore, uncertainty in SRM Isp as well as velocity uncertainty at SRM ignition (and other, smaller effects) will result in a residual Europa-relative of velocity of 100 m/s ±20 m/s at SRM Burnout.

Following the nominal SRM burn duration, we expect a period of time during which the SRM will continue to produce an exponentially-decaying thrust. While significantly lower than the nominal SRM thrust, the acceleration capability of the SRM casing by itself immediately following SRM burnout is significant and could result in recontact. To prevent recontact, jettison will be delayed until several seconds after burnout and an active separation system consisting of four small solid rocket motors attached to the SRM casing will be activated. When jettison does occur, the PDV will be commanded to thrust away from the SRM casing to further ensure safe separation.

Terrain Relative Navigation

After the SRM is jettisoned, the vehicle will slew to a vertical orientation and begin the Terrain Relative Navigation phase during which it will take several successive images of the surface of Europa to obtain a position estimate. TRN will be implemented in the Intelligent Landing System (ILS), a sensing system currently under development which is described in more detail in the next section. In addition to providing a position estimate, the ILS will also be used to provide horizontal velocity estimates throughout the remainder of DDL. Initial position estimates from the ILS require approximately 10 sec dedicated to imaging and data processing, though the system will continue to provide position and velocity estimates throughout the remainder of DDL.

Precision Landing Maneuver

Upon receiving an initial surface-relative position and velocity estimate from the ILS, guidance will perform the Precision Landing Maneuver (PLM). The objective of this maneuver is to steer the PDV so that, at the end of the maneuver, the PDV is vertically-oriented directly above the landing site at an altitude of 1000 m with zero horizontal velocity and vertical velocity of -30 m/s. When the PLM is complete, the PDV will descend to an altitude of 500 m to begin Hazard Detection and Avoidance.

Hazard Detection and Avoidance

When the PDV is at an altitude of 500 m and directly above the targeted landing location, it uses the 3D-imaging lidar to scan the landing site, construct a safe landing map, and select a landing location within that map. This activity must complete in three seconds, at which time the PDV will be approximately 400 m above the targeted landing location.

Once the Hazard Detection activity has finished, guidance uses the new, safe landing location to construct a guidance profile and steer the vehicle to a point above the targeted safe landing spot. The Hazard Avoidance Maneuver begins at an altitude of 250 m and completes at an altitude of 30 m with a vertical velocity of -0.5 m/s. The safe landing map, using the data from the 3D-imaging lidar, will be 100 m × 100 m and the vehicle has the capability to land anywhere within that map.

SkyCrane and Fly Away

Following completion of the Hazard Avoidance Maneuver, the PDV continues to descend at a rate of -0.5 m/s and, at an altitude of 21 m, the Lander separates from the Descent Stage and is lowered on a 10 m bridle to the ground. The Descent Stage continues to descend at -0.5 m/s until it reaches an altitude of 12 m. At this point, the Descent Stage detects touchdown by monitoring the commanded throttle level from the control system (the closed-loop control system adjusts the commanded throttle level to compensate for the weight reduction when the Lander mass is off-loaded by Europa). When Touchdown is detected, the bridle is cut and the Descent Stage performs the Fly Away maneuver until its fuel is fully consumed.

Intelligent Landing Sensing System

The Powered Descent Vehicle (PDV) is assumed to feature an Intelligent Landing Sensor System (ILS), comprising a camera, a dual-mode 3D imaging LIDAR, and a high-performance compute element. The ILS will provide key functionalities enabling autonomous safe and precise landing, namely Terrain Relative Navigation (specifically, map-relative localization, velocimetry, and altimetry), and Hazard Detection.

Map-Relative Localization

Following the SRM burn, the ILS will begin taking images of the Europan surface and search for feature matches between the descent images and an onboard map of the landing region. These feature matches will be fused with data from the inertial measurement unit (IMU) to provide estimates of spacecraft map-relative position, with a horizontal position accuracy requirement of 20 m (3σ) at 500 m altitude above the landing site. The onboard maps consist of a surface reflectance map and co-registered digital elevation map computed from stereo imagery acquired during the prior Europa fly-by mission.

The current MRL design is divided into two phases. A coarse matching phase, designed to reduce large initial horizontal position errors in the order of 2-3 km, searches for five large image templates over the entire map using Fast Fourier Transform (FFT) correlation. A batch estimator then fuses the information from three successive images to reduce the horizontal position error to less than 200 m. A subsequent fine matching phase trades a larger number of features against a smaller search region. During the fine matching phase, IMU and image matches are combined in an Extended Kalman Filter. The MRL design for Europa Lander is based on technology currently being developed to fly on the Mars 2020[4,5].

Velocimetry

In addition to feature matching between descent images and an a priori map, the ILS will extract information from image-to-image feature tracks. Together with scale information from the altimeter, they provide a six degree of freedom displacement measurement of the spacecraft between images, and hence bound position drift and provide accurate velocity information. The measurements from the IMU, the altimeter, and the feature tracks are combined in the MAVeN

(Minimal State Augmentation Algorithm for Vision-Based Navigation) estimation framework. MAVeN uses the feature tracks to update its current dynamic estimate along with the camera position estimate corresponding to an initial “keyframe”; this keyframe is switched from time to time as the number of tracked features decreases below a threshold.

Lidar for Altimetry and Hazard Detection

A dual-mode lidar is used to provide both altimetry and dense 3D mapping of the terrain at lower altitudes in a single low-SWaP (size, weight, and power) package. Beginning at an altitude of 8 km the lidar provides 1 Hz range measurements to aid MRL in resolving scale ambiguities. At about 500 m altitude, the lidar transitions to a wide-area mode 3D mapping sensor that is capable of acquiring range information over a 100 m × 100 m region at better than 5 cm ground sample distance; this results in a 3D map of the landing region that is 4M pixels in size. The map is then quickly evaluated to determine slopes and rock hazards that are on the scale of the lander, and those maps are combined to create a safety map based upon a predetermined cost function. A safe site is then selected from the list of identified candidates. Data collection, map generation, and safe site selection are allocated a total of three seconds in the DDL timeline, necessitating rapid lidar data collection and high-performance processing capability; this represents a significant challenge to the design of such a system which is further exacerbated by the extreme radiation environment in which the sensor must survive and operate. Following the safe site selection and divert, the lidar continues to provide altimetry information to the navigation system down to an altitude of 10 m.

CONCLUSIONS

Among the many difficulties of landing on Europa, terrain uncertainty, radiation, delivery uncertainty, and planetary protection are expected to pose unique challenges to the deorbit, descent and landing phase. In this paper we have proposed a landing system architecture which utilizes new and existing capabilities to increase the probability of landing successfully.

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REFERENCES

1 Campagnola, S., Buffington, B., Petropoulos, A., “Jovian Tour Design for Orbiter and Lander Missions to Europa,” AAS 13-494, 23rd AAS/AIAA Space Flight Mechanics Meeting, Kauai, Hawaii, February 10-14, 2013

2 Campagnola, S., Russell, R. P., “The Endgame Problem Part 1: V-infinity Leveraging Technique and Leveraging Graph,” Journal of Guidance, Control, and Dynamics, Vol. 33, No. 2, 2010, pp. 463-475, DOI 10.2514/1.44258

3 “Planetary Protection Provisions for Robotic Extraterrestrial Missions,” NASA Procedural Requirements NPR 8020.12D

4 Montgomery, J., Cheng, Y., Katake, A., Trawny, N., Tweddle, B., Zheng, J., and Johnson, A., “The Mars 2020 Lander Vision System,” Proc. International Planetary Probe Workshop, Laurel, MD, July 13-17, 2016

5 Johnson, A., Cheng, Y, Montgomery, J., Trawny, N., Tweddle, B., and Zheng, J., “Design and Analysis of Map Relative Localization for Access to Hazardous Landing Sites on Mars,” Proc. AIAA Guidance, Navigation, and Control Conference, San Diego, CA, January 21, 2016